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The causality between the rapid rotation of a sunspot and an X3.4 flare

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Abstract Using multi-wavelength data of Hinode, a rapid rotation of a sunspot in active region NOAA 10930 is studied in detail. We found the extra-ordinary counterclockwise rotation of the sunspot with positive polarity before an X3.4 flare. From a series of vector magnetograms, it is found that the magnetic force lines highly sheared along the neutral line accompanying the sunspot rotation. Furthermore, it is also found that the sheared loops and an inverse S-shaped magnetic loop in the corona formed gradually after the sunspot rotation. The X3.4 flare can be reasonably regarded as a result of this movement. The detailed analysis provides an evidence that sunspot rotation leads to magnetic field lines twisting in the photosphere, the twist is then transported into the corona, and finally flares are triggered.

Key words: Sun: sunspots - Sun: flares - Sun: magnetic fields

1 INTRODUCTION

It is now widely accepted that flares derive their power from the free energy stored in stressed or non-potential magnetic fields in the active regions (Zirin et al. 1973; Hagyard et al. 1984). But the process of rapid transformation of the magnetic energy into kinetic energy of particles, radiation, plasma flows and heat has not been very clear in detail. How the magnetic energy is stored and released still needs more observational evidences. Thus it remains a very important issue in solar physics.

There are several characteristics of active regions which are in favor of causing flares. If the active regions have strong magnetic gradients (Wang, et al. 1994, 2006), highly sheared transverse magnetic fields (Rausaria et al. 1993; Chen et al. 1994; Wang et al. 1996), emerging fluxes (Schmieder et al. 1997; Chen & Shibata 2000), and flux cancellation (Wang & Shi 1993; Zhang & Wang 2001; Zhang et al. 2001), flares are more often triggered. Besides the observations mentioned above, sunspot rotation (Evershed 1910,

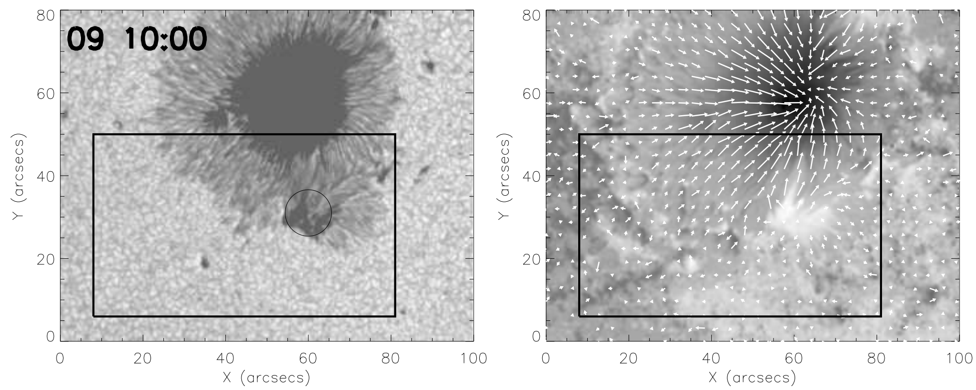

Fig. 1 The continuum intensity image (left panel) and vector magnetogram (right panel) of high resolution processed from Spectropolarimeter of SOT on 2006 December 9 respectively. Black (white) patches in the right panel indicate the negative (positive) polarity. The circle is placed at the rotating sunspot and the box outlines the field of view of Fig. 3.

the energy is released later via flares (Stenflo, 1969; Régnier et al. 2006; Yan et al. 2007, 2008). Rotation of a sunspot in the photosphere may cause an injection of twist into the corona (Tian et al. 2006), which was proven by the TRACE EUV images, also by the S-shaped or inverse S-shaped structures in the soft X-ray images of Yohkoh/SXT (Canfield et al. 1999, Pevtsov 2002).

In this paper, we describe the rapid rotation of the sunspot and the relationship between the sunspot rotation and the X3.4 flare. An emphasis on the possible causality of the flare eruption is made by tracing the evolutions from the photosphere to the corona of this active region. This may add one significant and reliable evidence to an argument that the rotation motion trigger the flare.

2 OBSERVATIONAL DATA

The data used in this paper contain those detailed as follows: 1. Continuum intensity images and vector magnetograms from Spectropolarimeter (SP) of Solar Optical Telescope (SOT, Tsuneta et al. 2008), and X-ray images from the X-Ray Telescope (XRT, Golub et al. 2007) aboard on Hinode (Kosugi et al. 2007); 2. Soft X-ray flux of GOES12.

In this paper, we used the Fast Map of SP data. The reduction of spectropolarimetric data from Hinode is carried out by the radiative transfer equation derived by Unno (1956) and improved by Landolfi et al. (1982), and a Milne-Eddington atmosphere is assumed. The 180 degree ambiguity is resolved by comparing vector magnetograms with the potential fields (Metcalf et al. 2006).

3 PROCESS OF AN X3.4 FLARE

NOAA 10930 is a bipole active region, which was composed of a big sunspot with negative polarity and another small sunspot with positive polarity (see Fig. 1). There were many B class flares, C class flares, and two X class flares occurring in this active region recorded from December 9 to 14. Here, we only analyze the prominent X3.4 flare in detail for the purpose.

According to the soft X-ray emission from GOES 12 (see Fig. 2), there was an X3.4 flare in this active

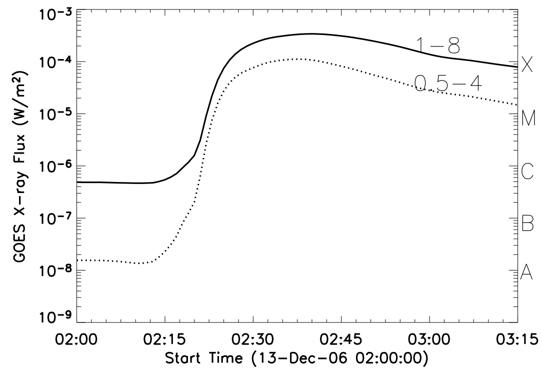

Fig. 2 Evolution of soft X-ray emission (Solid line: 1-8 Å. Dashed line: 0.5-4 Å) for the flare on 2006 December 13 from GOES 12.

By observing the evolution of this active region, we noted that the small sunspot presented an extraordinary counterclockwise rotation. Figure 3 shows high resolution continuum intensity images (left panels) and vector magnetograms (right panels) with transverse components overlying longitudinal ones gotten from Spectropolarimeter of SOT. From the evolution of the continuum intensity images, one can see that the small sunspot with positive polarity not only moved from the southwest of the big sunspot to the southeast but also rotated rapidly around its umbral center. Referring to the light fibrils connecting the umbra of the small sunspot in the continuum images, one can trace its rotation process. The center of the circle which contains all the umbral features of the small sunspot is labeled as "$O1$" to illustrate the reference frame. The light fibrils also rotated around the center of the sunspot umbrae, one can evaluate their motions and obtain rotation angle and speed easily. Arrows labeled by numbers indicated different penumbral fibrils which are used for tracing the change of the rotation. In this figure, the dashed lines in the small sunspot indicate the radius of the circle. The rotation angle increased during the evolution of four days and reached 259 degrees (see Fig. 4a). Two peaks appeared in the curve recording the rotation speeds on Dec. 11, 12 (see Fig. 4b). Because the time resolution is not so high, we only get relatively rough average of the rotation speed. Following the sunspot rotation, magnetic force lines between the two sunspots around the magnetic inversion line became sheared correspondingly (see the right panels of Fig. 3). The transverse magnetic fields took on spiral pattern around the center of the umbrae of the rotating sunspot. The average strength of transverse magnetic fields in the box in Fig. 1 increased rapidly before December 12 (see Fig. 4c). Simultaneously, the expansion of the magnetic field-covered area (the box labeled region in Fig. 1) related to the rotating sunspot can be seen. The negative magnetic fluxes increased from December 11 to 13. However, the positive magnetic fluxes first increased and then decreased rapidly (see Fig. 4d). After we checked the magnetograms, we found that there are two reasons accounting for this phenomenon. On one hand, there are many samll positive magnetic fluxes around the main positive sunspot diffused out of the region following the main positive sunspot emergence. On the other hand, some of the longitudinal magnetic fields may be transfered into the transervse ones accompanying the sunspot rotation. During five days' rotation of the sunspot, the X3.4 flare erupted as mentioned above.

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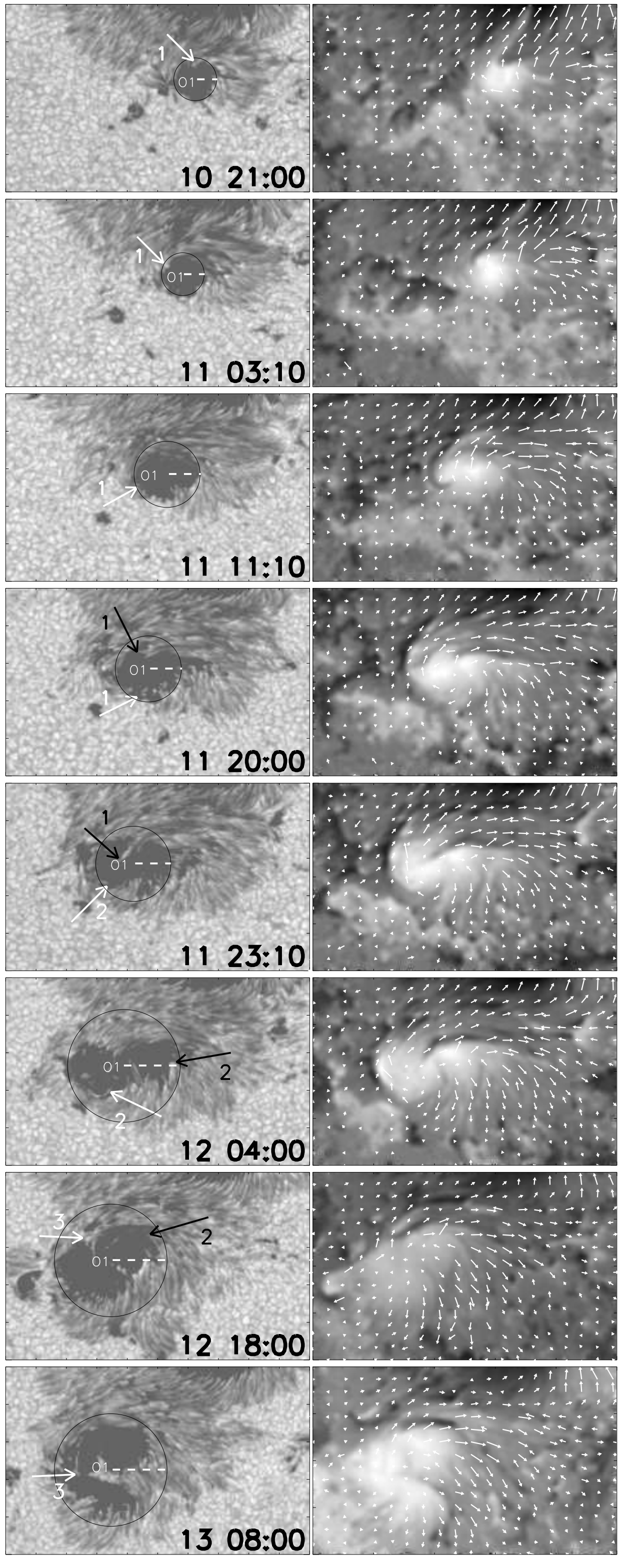


Fig. 3 Rapid rotation of sunspots seen in the sequence of the continuum intensity images and vector magnetograms from Spectropolarimeter of SOT. The circle is including the umbra of the rotating sunspot. The arrows in the left panels are specified in detail in the text. The field of view is $75'' \times 45''$.

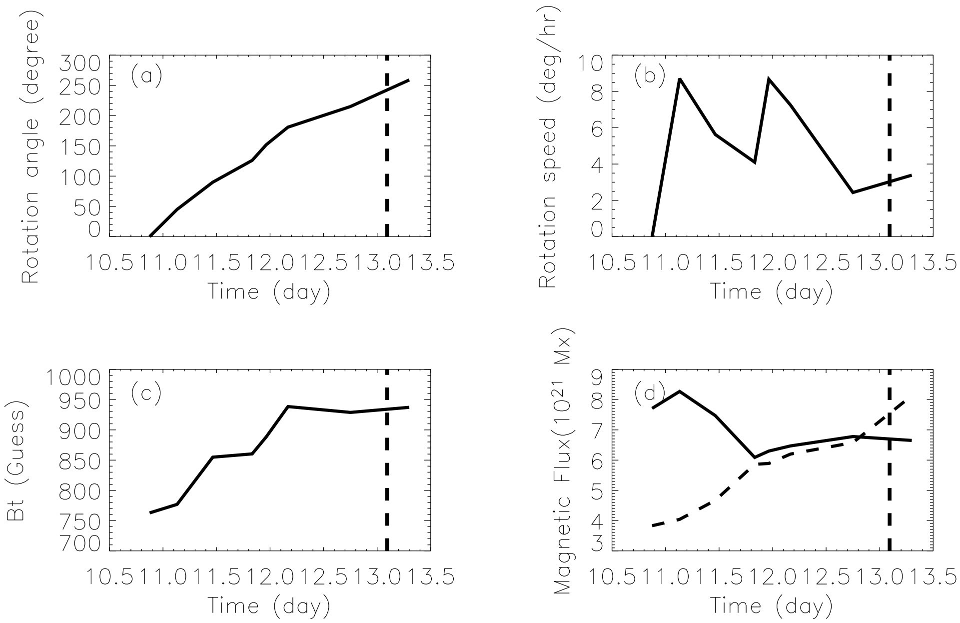


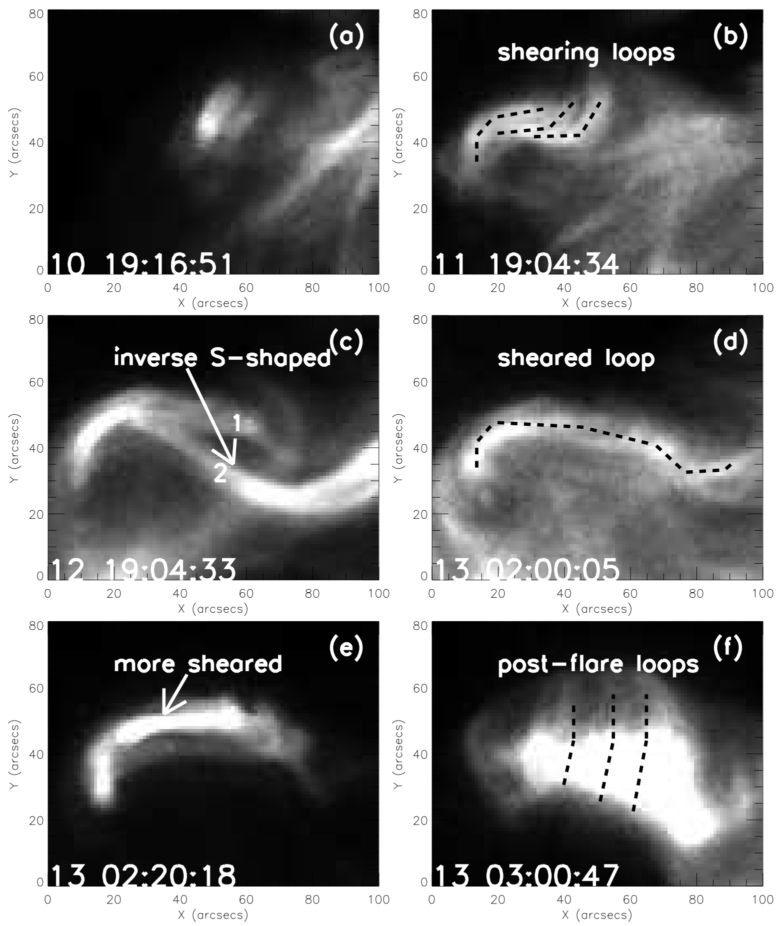
Fig. 4 Plots showing the evolution of the rotation angles (a), rotation speed (b), the average strength of transverse magnetic fields (c), and the positive (solid line)/negative (dashed line) magnetic fluxes (d). The vertical dashed lines denote the beginning time of the X3.4 flare.

of high temperature during the sunspot rotation. One can see the formation process of the sheared loops structure from December 10 to December 11. The three dashed lines in Fig. 5b denoted the three shearing loops. An inverse S-shaped structure appeared on December 12 accompanying the sunspot rotation (see Fig. 5c). The inverse S-shaped loop and another loop are signed by 1 and 2 respectively in Fig. 5c. Before the X3.4 flare, the two loops almost merged into one sheared loop denoted by the dashed curves in Fig. 5d. During the X3.4 flare, the loops became more sheared at 02:20:18UT and the width of loop became narrow pointed by a white arrow in Fig. 5e. After the flare, the sheared loops disappeared and became potential post-flare loops denoted by the dashed lines in Fig. 5f. The sheared and the inverse S-shaped structures are in favor of the occurrence of magnetic reconnection in common sense (Ji et al. 2007, Pevtsov 2002). The foot points of these loops can be seen rooted in the magnetic condensed region. Therefore the rotation can shear these loops correspondingly, then triggered the eruption.

From the above descriptions, one can not help thinking of this: the sunspot rotation caused the loop footpoints moving and the magnetic field lines shearing. The lower magnetic field lines of loops were twisted in the photosphere and then the twist was transported into the corona. It is worth pointing out that Gibson et al. (2002, 2004) observed magnetic flux ropes in the corona and simulated the rotation of the sunspot. They found that the sunspot rotation can form an S-shaped structure in the corona. In this paper, we identified the result again from observation.

4 SUMMARY AND DISCUSSION

In the above sections, we have investigated the active region NOAA 10930 from 2006 December 10 to 13 in detail. From the evolution of this active region, we have found the rapid rotation of the small sunspot.



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More important is that we combine these findings and trace the causality chain from the sunspot rotation to the flare eruption by using those high spatial resolution images. Therefore, we can conclude that the rotation produces and transports the twist of the loops through their legs to tops where the twist is evidenced by the XRT observations. Thus one can get the result that the sunspot rotation serves as the driver for both twisted magnetic loops formation and their non-potential eruption. Thus, the chain of causality for the X3.4 flare eruptions can be traced as follow: the rapid rotation of the sunspot, the evolution of their transverse magnetic fields, and the corresponding evolution of configuration of magnetic loops in corona, and then the eruption. All of these provide a reliable evidence that photospheric motion makes magnetic loops twist from the photosphere through the chromosphere into the corona, and then flares are caused.

As is also well known, the Coriolis force can make sunspots rotate in a clockwise (counterclockwise) direction in the northern (southern) while the differential rotation gives rise to the reverse motion. Bao et al.

tial rotation, they have also analyzed the α-effect, surface flow, and magnetic reconnection. However, many different viewpoints exist in the literature. For example, Brown et al. (2003) thought that the differential rotation does not play a major role in producing sunspot rotation. They suggested that the photospheric flow and flux-tube emergence may be responsible for sunspots rotation. Su et al. (2008) proposed that Lorentz force may be a possible driving force for sunspot rotation. Following the development of the technology and theory, the mechanisms of sunspot rotation are expected to be solved in the future.

ACKNOWLEDGMENTS

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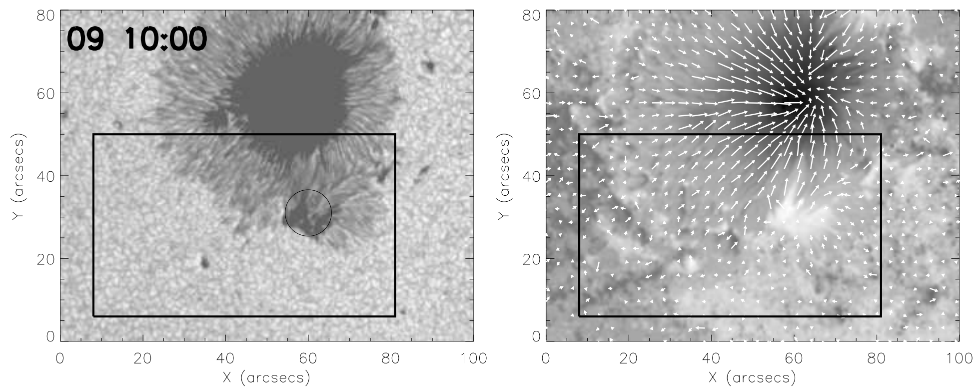

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3 PROCESS OF AN X3.4 FLARE

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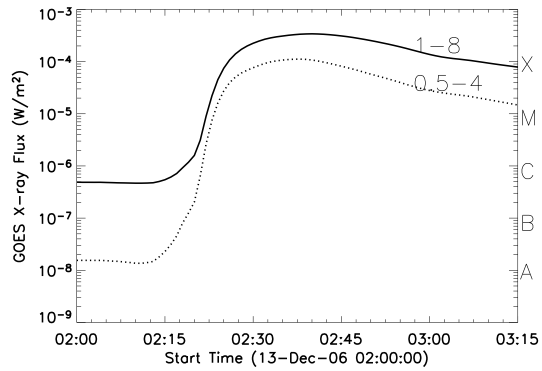

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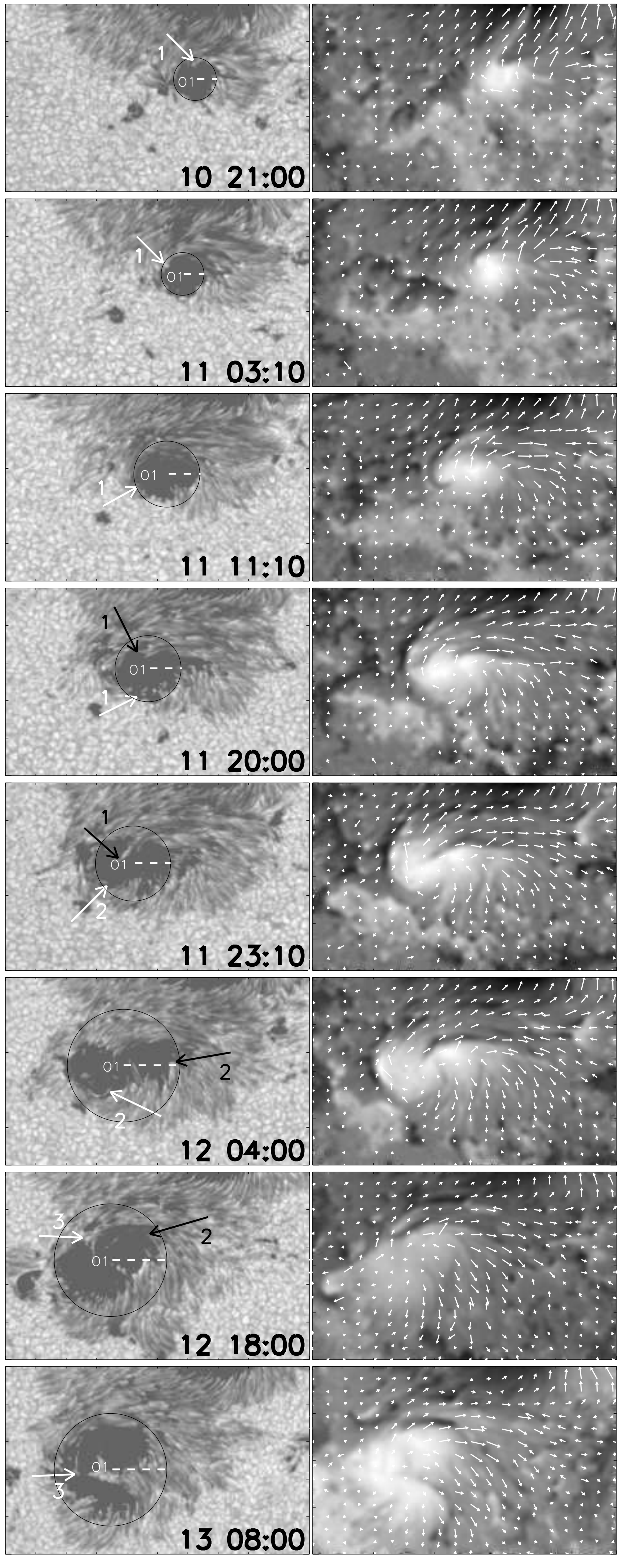

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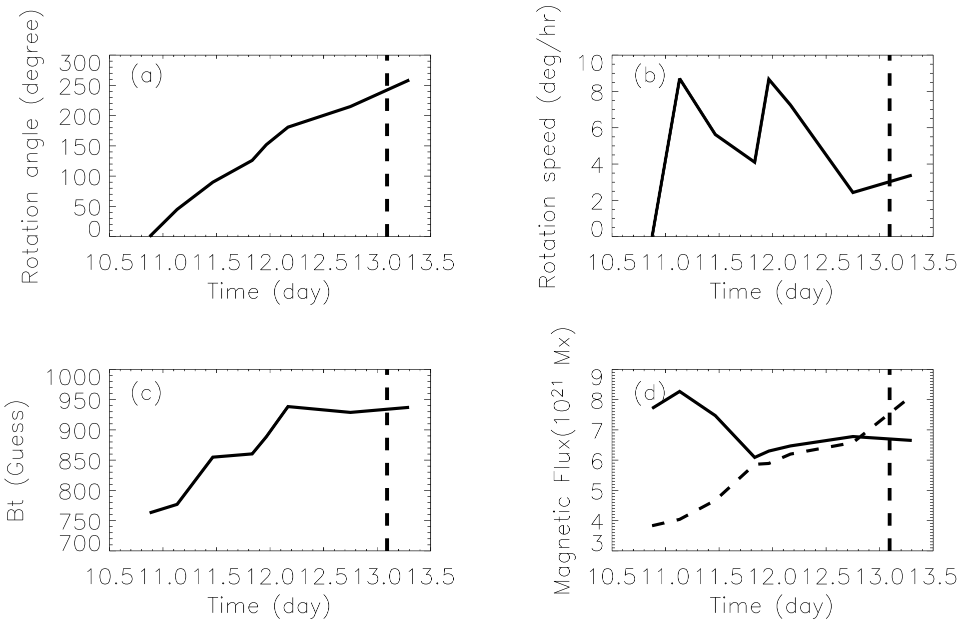

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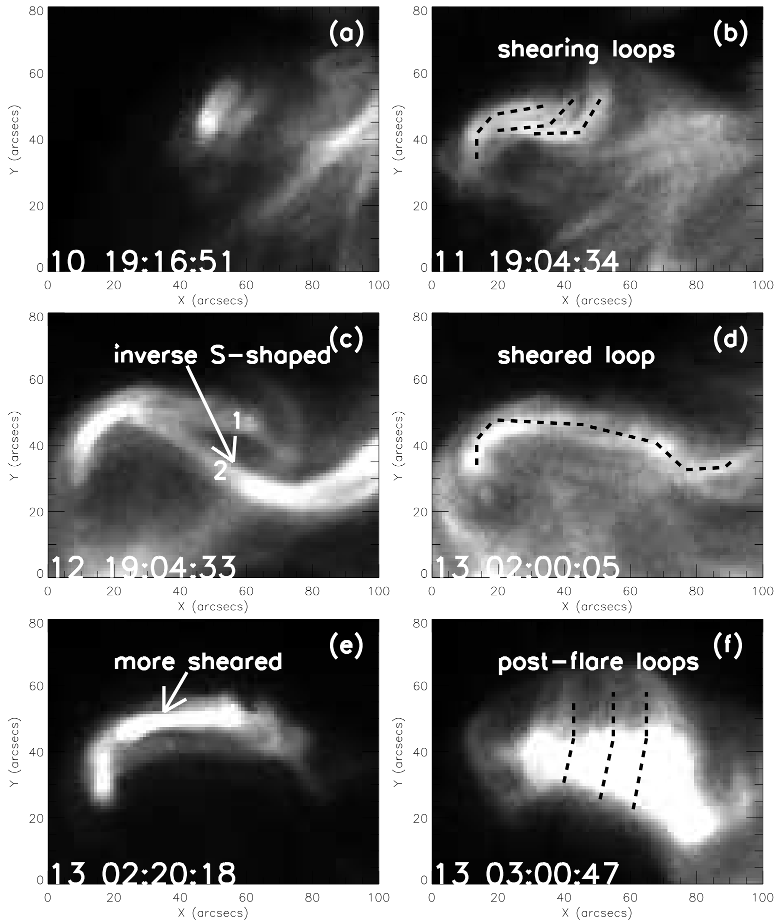

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